An algorithm for root cause analysis integration based on OTSM-TRIZ: Complex problem analysis

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1 INTRODUCTION

Today maintenance problems are more and more complex, mixing technical, economical and human variables, due to continue changes in the maintenance (Crespo, 2007), the new generation of methods and tools assume a relevant connotation to identify failures and propose new solutions concepts for different kind of problems. There are many different methods for addressing maintenance issues in the literature (Barberá, 2010). The most important ones are classified according the complexity, quality of required information and applicability of their results (Viveros et al., 2012; Barbera et al., 2012a). Root Cause searching techniques are frequently used by companies to understand the problem context: 5 Why Analysis, Logic Tree, Current Reality Tree (CRT), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Pareto Analysis, Bayesian Inference and Ishikawa Diagram (Cause-Effect). These methods are useful to identify problems, failure modes and fundamental causes of failures or recurrent problems, which need to be corrected. However, all these methods share the same weakness, i.e. solution concepts generation is usually demanded to poorly supported brainstorming sessions (Viveros et al., 2012). For this reason, the integration of structured means for idea generation to improve the efficiency of current Root Cause Methodologies remains a latent issue (Latino, 2010).

Barbera et al., (2012b) and Li and Gao, (2010), proposed a role for the root cause analysis according to maintenance management stages, so as to identify the appropriate tool in the whole maintenance process.

The Theory of Inventive Problem Solving (TRIZ) was created by G. Atshuller (1984), with the aim of creating a systematic approach to resolve problems and identifying the creative patterns used by successful inventors. The usability and repeatability of the classical TRIZ tools demonstrated to be high in clearly defined problem context (Cavallucci & Khomenko, 2007). However some limitations exist to resolve complex problems when technical and administrative variables appear together. OTSM-TRIZ was created as an evolution of the theory, whose aim is to provide instrument to increase the efficiency of the solutions in case of non-typical and complex problems (Cavallucci & Khomenko, 2007).

The weakness in the RCA methodologies can cause considerable losses in terms of reliability, and consequently, even monetary losses for companies. The opportunity to integrate RCA methodologies with the Theory of Inventive Problem Solving (TRIZ) as a means to overcome the abovementioned limitation triggered the research activity described in this paper.

The research activity has been carried out in collaboration with the Chilean company ARAUCO S.A (www.arauco.cl), one of the major forestry companies in the world and Federico Santa Maria University. The authors' algorithm is the result of ARAUCO training program to increase the skills and capabilities with RCA and problem solving for more than 150 employers. This training program was a good opportunity to assess the effectiveness and applicability of the proposed algorithm into a real industrial environment.

2 LITERATURE REVIEW

2.1 *Root Cause Analysis (RCA)*

Proactive Maintenance uses tools such as Root Cause Failure Analysis (RCFA), Failure Mode and Effects Analysis (FMEA), Criticality Analysis (CA), Acceptance Testing (AT) and Age Exploration (AE). Some authors make a distinction and identify a sub-branch in the Proactive Maintenance, called Radical Maintenance (RM), which involves the detection and prediction of root cause failures, and later takes appropriate measures to eliminate the root causes or conditions that induce them (Gao, 2005; Gano, 2007).

The RCA revealed to be useful in various practical applications, thanks to its capability of: i) Proactively avoiding recurrent failures of high-impact operating and maintenance costs; ii) Reactively solving complex problems that affect an organization; iii) Analyzing repetitive failures of equipment or critical processes; iv) Analyzing human errors when designing and implementing procedures.

The benefits brought by the use of RCA are (Rasmuson, 2008; Flaus, 2008): i) Reduction of the number of incidents and failures; ii) Reduction of expenses and deferred production associated with failures; iii) Improvement of reliability, safety and environmental protection; iv) Improvement of efficiency, profitability and productivity.

There are a wide variety of tools and methods to determine the root causes of certain events or failures. These vary in complexity, quality of the information required and applicability of their results. In general, the most commonly used are shown in Table 1.

Table 1. Methods to determine root causes.

	Methods to determine the root causes
Quantitative	Fault Tree Analysis (FTA)
	Pareto analysis
	Bayesian inference
Qualitative	Analysis of the 5 whys
	Ishikawa diagram
	HAZOP
	PROACT

An important detail is that the failure event has to be a factual event not an assumption, so to be easily recognized in the system. Also, the detail level of the root cause is relevant to understand the real cause of the problem and provide better solution. For these reasons, the selected RCA method is PROACT, which organizes the logic structure of the chain of causes and effects, from the event of failure or problem until the basic causes that produce it (deductive analysis).

Finally, the logic tree develops into the root cause of each failure mode. Typically, there are three types of causes:

- Physical: Failure mechanism of the component. It is the cause that creates the failure directly.
- Human: Human error that impacts directly or indirectly the failure occurrence.
- Latent: Demonstration of the organizational processes that explain the occurrence of human root causes. Only its eradication guarantees that the failure is not repeated.

2.2 *Classical TRIZ: Characteristics, theoretical framework*

TRIZ (a Russian acronym for Theory of the Solution of Inventive Problems) is a reasoned set of assumptions, models and tools originally developed by Altshuller (1984) on the basis of patent information. Currently applied in the design field to solve technical problems and increase the quality of solutions concepts, TRIZ is founded on three main concepts.

i. The Law of Engineering System Evolution (LESE): any technology follows a finite number of patterns to evolve. There are 8 laws of Engineering System evolution; among them, an important concept is the so called law of Ideality, meant as the general trend to improve performance while reducing the consumption of resources and/or its harms (Altshuller, 1984; Svransky, 2000). The law of Ideality is frequently used to understand the technological maturity of the system.

ii. Contradictions: A technical contradiction takes place when two parameters are in conflict with each other, typically two requirements. Improving one parameter implies the worsening of the other. In general, there are three levels of description for contradictions: Physical contradictions are the contradictions expressed as opposite values for the design variables of the system under analysis; technical contradictions are described with two technical parameters related to system requirement in conflict; administrative contradictions are related with high level descriptions of the design problem, with no detailed knowledge about the influent variables. The resolutions of contradictions are supported by different tools. (Altshuller, 1984; Svransky, 2000).
iii. Specific Situation: The technological systems evolve according to the specific availability of resources that characterize the system environment.

These concepts are useful when the system and contradictions are clearly defined. Classical TRIZ tools attempt to resolve only one contradiction at a time. Besides, complex problems are characterized by a high number of contradictions and in these situations Classical TRIZ can miss relevant information of the problem.

2.3 *OTSM-TRIZ and network of contradictions*

OTSM-TRIZ is an evolution of classical TRIZ: proposed by Nikholai Khomenko aims at managing complex interdisciplinary problems (Cavallucci & Khomenko, 2007). OTSM-TRIZ adds new models and tools to Classical TRIZ and a new procedure to describe the problems starting from an initial high-level problem. This procedure is called Problem Flow Network (PFN) and brings to the identification of the complex and multidisplinary nature of problems through the so called Network of Contradictions (NoC).

One of the main contributions of this methodology is the possibility to analyze complex problems by identifying and creating relations between all the variables involved in the problems at different levels of the analysis. Indeed, the complexity further increases when various knowledge domains, as well as technical-social-economic-environmental issues, are involved (Nikulin et al., 2012).

Network of Contradictions (Baldussu et al., 2011) requires distinguishing two different classes of parameters: Control Parameters (CPs) that can be leveraged by decision makers in order to obtain a specific outcome, and Evaluation Parameters (EPs), that allow to measure the positive or negative effect of the decision. Figure 1 shows structure model of the elementary contradiction according

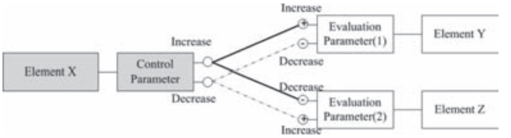

Figure 1. Elementary model of a contradiction according to the OTSM-TRIZ formalism.

to OTSM-TRIZ: If the value of the Control Parameter increases, the Evaluation Parameter (1) improves, causing a positive effect in the Element (Y), but the Evaluation Parameter (2) worsens and causes a negative effect to the Element (Z).

3 ALGORITHM TO INTEGRATE RCA AND OTSM-TRIZ

The following original algorithm attempts to integrate the RCA tools and OTSM-TRIZ to address the weakness previously mentioned. The algorithm is divided into 6 steps:

Step 1: Description of the system and selection of the part: In this step it is necessary to identify the function and behavior of the system. The EMS model provides an understanding of the functions at different levels. The additional description of the Minimum Technical System supports the user to identify parts of the system by function, creating a hierarchical and structured diagram. The level of detail depends on the nature of the failure and on the possibility to attribute its responsibility to a specific subsystem according to the user's knowledge on the situation. Selection of the part for analysis can be done using different decision making methods as Critical Analysis (CA) considering frequency and consequence of the failure on the system.
Step 2: RCA and failure mode: Selected a part of the system described in step 1, RCA analysis has to be done so as to identify the failure mode of the part. Each failure mode of the system has to be described using RCA (PROACT); the user has to classify each cause according to the different level (Physical, Human, Latent) with the aim of simplifying the formulation of contradictions.
Step 3: Network of contradictions: This step is focused on the creation of the Network of Contradictions according to the different causes identified at step 2. The human causes are the link between contradictions on technical and organizational level. To formulate contradictions, recommendations are given below:

i. For each "physical root cause" it is necessary to identify the technical EPs related to its impact.

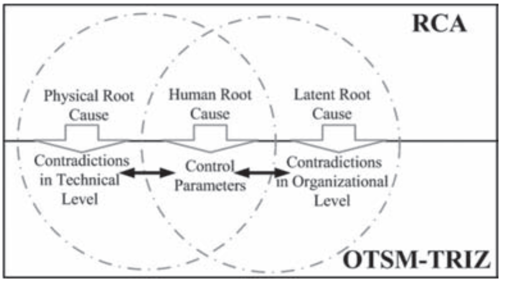

Figure 2. Pictorial representation of the proposed integration of RCA and OTSM-TRIZ.

ii. For each "human root cause" it is necessary to identify CPs; these can be at technical or organizational level.
iii. For each "latent root cause" it is necessary to identify the organizational EPs related to its impact.

Step 4: Resource definition: This step requires the identification of the resources involved or related with the system under analysis. TRIZ-based classification of resources represents the basis for resolving the contradictions.

i. Material: what composed a system and its surroundings. Readily available resources include raw materials or semi-finished products, as well as waste or absence of a substance (e.g., sand and chemical).
ii. Energy: any kind of energy inside or around a system (e.g., gravitation, thermal); energy human resource, when humans are contributing with the activity of the process.
iii. Information: any perceptible information about the system (e.g., properties of the system and temporary information, information flow).
iv. Time: any kind of time including intervals (i.e. monitoring time, time between failures).
v. Space: any free/unused space in a system or in its environment (e.g., the spare wheel space in a car).

The main objective of this step is to identify the possibility to use these resources in the solution concepts to solve the problem and/or failure.

Step 5: Partial solutions: this step suggests the use the TRIZ tools for resolving the maximum number of contradictions as possible according to the available resources.

Step 6: Implement solutions and evaluation: The purpose of the last step is to measure the impact of the solution in the system, many index can be created to measure the impact of the solutions (Viveros et al., 2012, Nikulin et al., 2012); even EPs can be used to measure the impact of the solution in the system to rank.

4 CASE STUDY

In this section a case study attempts to clarify the usability of the proposed algorithm. The Energy Plant Process of Chilean Company ARAUCO S.A. was analyzed to validate the effectiveness of the algorithm. Actually the energy plant process corresponds to one of the most beneficial process for the company mainly for the high price of the electric energy in Chile (app. 25 cent/kWh). The actual plant has a production capacity around 25 [Megawatts], the energy is distributed to the process plant and the excess energy is sold to other companies.

The company introduced several changes in the last years: one of this change correspond to a training program to increase the capabilities of their employees in problem identification and solutions. The case study discussed in this section is part of a research project, between Federico Santa Maria University and ARAUCO S.A.

Step 1: Description of the system and selection of the part: The actual system under analysis is the boiler of the company's energy plant.

The boiler system is described using the 3 main sub-functions, each functions was represented using the MTS model identifying different parts. Figure 3 shows the schematic representation of the boiler system.

System availability is around 0.980–0.985 and it needs to be improved at least to 0.990. The company identified the most relevant failure modes as related with the nozzle of the boiler (the selection of the part was based on the level of relevance of the failure and impact on the system).

Step 2: RCA and failure mode: The identification of the different causes of failure has to be provided according to the part of the selected system, the nozzle fracture can be described as the main failure mode of the analysis. The logic tree helps to classify the causes into different categories, such as physical, human and latent causes. Five main physical causes are indentified, four human causes and four latent causes (Fig. 4).

Step 3: Network of contradictions: The Logic Tree was divided in two parts: technical and organizational issues. The human root causes are the link between contradictions in the differents levels (Figs. 5 and 6).

i. Contradiction on technical level: For each "physical root cause" a technical EP was identified; as well, for each "human root cause" a CP was identified on technical level. In this ways it is possible to manage the influence of the CP in the system by humans decision (Fig. 5).
ii. Contradiction on organizational level: For each "latent root cause" an organizational EP

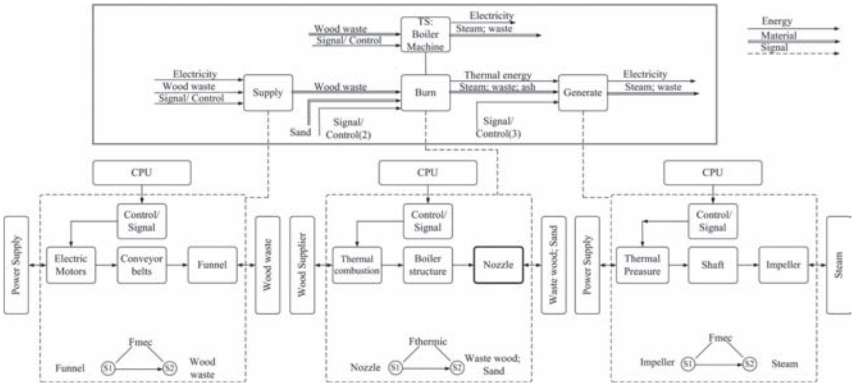

Figure 3. Description of the system.

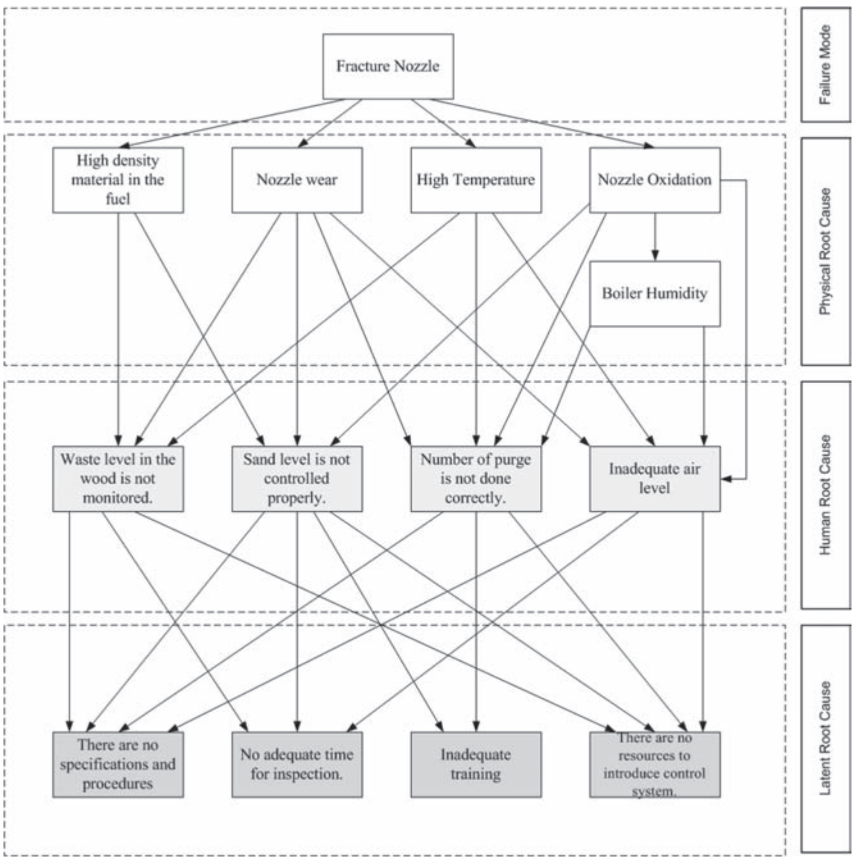

Figure 4. RCA using PROACT for the case study.

was identified; as well, for "human root cause" a CP on organicational level was indentified (Fig. 6).

To understand the influence of the contradictions in the system two examples are included:

i. If the Decision Makers (DMs) decided to increase the sand in the boiler (CP2) then the temperature combustion increase (EP3) (desired effect), but the number of cracked nozzle increases too (undesired effect) (EP4).

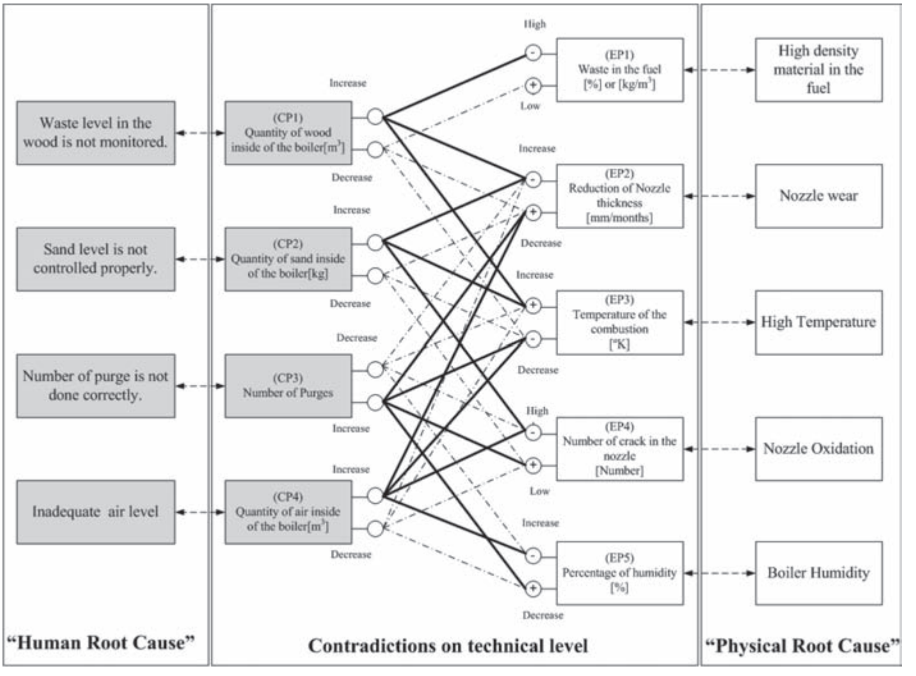

Figure 5. Contradictions on technical level: Technical evaluation and control parameters.

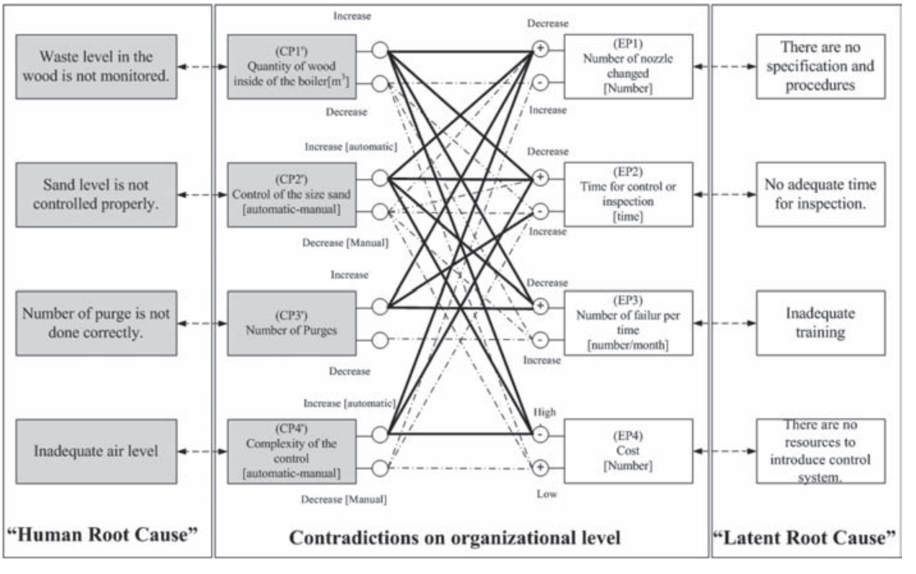

Figure 6. Contradictions on organizational level; Organizational evaluation and control parameters.

ii. If DMs increase the number of purges (CP3) then the wear in the nozzle is reduced (EP2) (desired effect), but the temperature of the combustion decreases (Undesired effect) (EP3).

Figure 5 shows the contradictions on technical level inside the system and interpretaton of the teamwork or DMs over the EPs. Figure 6 represents the contradictions on organizational level. Figures 5 and 6 have the common "human root causes", but the control and unit of measure can be changed according to the nature and level of the contradictions.

Step 4: Resource definition: The resources of the companies have been classified as shown in Table 2.

The list of resources can be useful at moment to create the partial solutions on the system.

Step 5: Partial Solutions (PS): The partial solutions of the contradictions are focused on increasing the ideality of the system; in this case study, this corresponds to increasing the availability of the boiler while consuming the minimum amount of resources. Several partial solutions are provided to achieve this goal with respect to the number of contradictions:

i. *PS1* (*Waste level in the wood not monitored*)*:* To solve these contradiction Inventive Principles were used: Principle 10 (Anticipation) and 24 (Mediator), create a preventive intermediate system to remove the high density material (Barberá et al., 2012a).

ii. *PS2* (*Sand level is not controlled properly*): To solve the contradiction the 76 standard solutions were used, and more specifically the class four standards (measurement and detection standard) (Altshuller, 1984): auxiliary system to control the size of sand.

iii. *PS3* (*Number of purges*)*:* To solve the contradiction again the 76 standard solutions, class were applied: Auxiliary system to control the number of purges calculated according to the new performance of the boiler, the number of purges has to be established and controlled over time.

iv. *PS4* (*Inadequate level of air*)*:* The level of air in the boiler has to be correctly calculated according to the new performance. In this moment the company has an automatic control system for this parameters.

Step 6: Implement solutions and evaluation: The implemented solutions used in this case study correspond to the PS2 (Waste level in the wood not monitored), PS3 (Number of purges) and PS4 (Inadequate level of air). The first work done by the team was to monitor the quantity of sand for 3 months. The preliminary results are: the average of the sand used in the process is 4.06 [kg/ton of wood] monthly.

The following program was integrated by the company:

i. Filling boiler standardization by working day.

ii. Monitoring size of sand before the combustion process (20% of the sand inside of the boiler has to be higher than 1.7 m).

iii. Standardization of the number of purges (6 time per day)

iv. Level of air in the boiler was recalculated according to the previous changes.

The most important results correspond to the reductions of the quantity of sand used in the process, in the following four month, the consumption of sand was reduced to 3.44 [kg/ton of wood] saving the 15% of sand costs, the availability of the system increase until 0.988 close to the expected goal (not considering PS1). However, the solutions were considered successful by the company, because there were no additional costs and all solutions used available resource of the company (human resources, control and monitoring equipment).

Table 2. Resource classification for case study.

Resource type	Description
Material	Wood, water, steam, wood chips, waste of wood, Sand, air extractors, chemical, fuels, dust.
Energy	Electrical energy produced by the biomass plant owned by the company, thermal energy.
Information	Number of purges per day, number of stops per day, energy quantity, level of sand in the boiler, monitoring system.
Information human resource	Workers' skills, monitoring and controlling sytem.
Time	Time in storage, time for maintenances, equipment starting-time, inspection time, time to replacement, availability.
Space	Operation area, space around the company production plant, boiler area.

5 DISCUSSION

Finally, for the main problem four partial solutions were proposed; the combinations of all the solutions help to address the main problem in an effective way. However, it is important to add some considerations with respect to the repeatability of the algorithm such as: the competences of the team work to develop the RCA and identification of contradictions, the time consumption to develop the analysis can be high is the teamwork doesn't have previous experience with TRIZ. The decision process of the critical part or system can be supported by using additional decision tools as Pareto and Critical Analysis.

System analysis helps to describe in a visual way many parts of the system: the benefit of using this kind of diagram is the possibility to clearly understand the function and sub-functions of the system, such that more failure modes can be taken into account for the analysis. The Authors consider Logic Tree PROACT one of the best methods to integrate the NoC.

6 CONCLUSION

The research described in this paper proposed a systematic algorithm to identify and solve complex problems based on failure mode using RCA and

OTSM-TRIZ. The contribution of the papers is related to the identification of contradiction on different levels using RCA methodologies. Moreover, the decision makers can see in a visual diagram the consequences of their problems. The identification of the human causes as control parameters helps to notice the influence of the human decision on technical and organizational level. Regarding the algorithm effectiveness, the obtained results have been evaluated as effective, but additional case studies should be planned to test the algorithm robustness.

With respect to the training program and the development of case studies to create a correct integration between TRIZ and Maintenance methodologies, it is necessary to standardize the context and language because some terms have different meanings, thus creating some confusion in the usability of the algorithm. The results of the case study were considered successful, because it was not necessary to introduce new expenses to implement the solution. The authors consider this study as a starting point to build a software application capable to guide the analysis using system analysis, problem identification and problem resolution following a systematic and structured approach.

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